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Analysis and measurement of a Zener diode voltage-reference

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ANALYSIS AND MEASUREMENT OF A ZENER DIODE VOLTAGE-REFERENCE

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ABSTRACT

Output voltage sensitivity equations are derived for a zener voltage-reference circuit. The circuit consists of a DC-DC converter, a voltage-resistor current generator, and a zener diode. The performance of the voltage-reference is calculated using the sensitivity equations and compared to measurement data taken from a laboratory model of the circuit. The results are in reasonable agreement.

It was concluded that with careful selection of components, two of three major sources of error can be predicted and controlled; these are changes due to input voltage and changes due to temperature. The third, changes due to time, requires calibration against a voltage standard.

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I. INTRODUCTION

Many electronic devices such as voltmeters, bridges, and signal conditioners depend upon a voltage-reference for accuracy. The reference should be independent of temperature changes and time. Other desirable features of a voltage-reference include short-circuit protection, low noise output, small size, light weight, high efficiency and low cost.

The limitations of standard cells for use as a voltage-reference are well documented [2,8]*. They are sensitive to rough handling, shock, and vibration; their temperature range is limited to 4 to 40°C; they are subject to hysteresis effects caused by abrupt temperature changes; and they are sensitive to load conditions. A load current of only one microamp can drop the cell EMF by 500 microvolts.

The merits of the zener reference circuit are also well documented [1,3]. Briefly, they offer small size, reliability and ruggedness. They are not without their disadvantages for they require an external power source and have unexplained time drifts.

It is not the purpose of this paper to offer a replacement for the standard cell as a voltage standard but to show some of the more important considerations in the design of a zener reference circuit. These considerations are shown by analysis and measurement of a typical circuit's performance.

The circuit was used in an aircraft application. The specifications for the design are given in Table I.

*Numbers in brackets refer to references--section VIII.

TABLE I

REFERENCE SPECIFICATIONS

o	Input Voltage	28 $\pm$ 10%	VDC
o	Power Consumption (Max.)	5	Watts
o	Size (Max.)	15	Cu. In.
o	Weight (Max.)	0.5	Lb.
o	Temperature Range (Ambient)	-40 to + 80	^{o}C
o	Isolation	100	VDC
o	Noise (Peak-to-Peak)	500	Microvolts
o	Calibration Cycle	168	Hours
o	Accuracy	$\pm$ 0.01	%
o	Load (Minimum)	10^6	Ohms
o	Output Voltage	8.5 to 12.5	VDC
o	Warm-Up Time	10	Minutes
o	Overload Recovery Time	10	Seconds

II. CIRCUIT DESCRIPTION

Figure 1 shows a block diagram of the zener reference circuit. Each block is described below as to composition and function.

(A) Isolator: The isolator is a DC-DC converter whose unit specifications are stated in Table II.

TABLE II

ISOLATOR (DC-DC CONVERTER) CHARACTERISTICS

Manufacturer	Technetics
Model Number	11352/7398-001
Input Voltage	24-32 VDC
Input Current	360 mA (Max.)
Output Voltage	20 VDC
Output Current	150 mA (Max.)
Ripple	480 mV p-p (Max.)
Regulation	
Line	0.037 (Volt/Volt)
Load (½ Load to Full Load)	5.34 (Volt/Amp)
Temperature Coefficient	± 100 PPM/°C
Stability	± 1%/1000 Hours
Isolation	200 VDC

The function of the unit is to provide DC isolation between the input and output circuits. This allows the reversal of the reference output voltage for those applications requiring a negative reference voltage. Figure 5 shows the primary circuit block diagram. Voltage V_4 is isolated from the primary input source V_5.

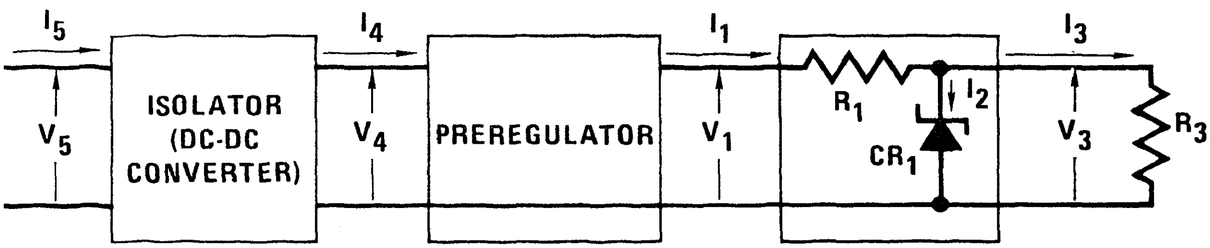


FIGURE 1. ZENER REFERENCE CIRCUIT

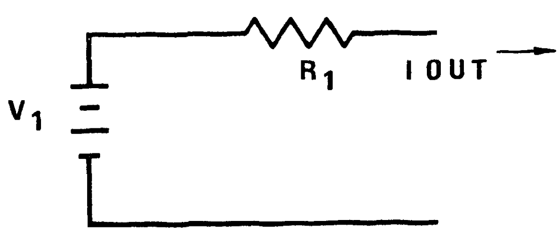


FIGURE 2. VOLTAGE-RESISTOR CURRENT GENERATOR

(B) Preregulator: Referring again to Figure 1, the center block is a regulator with specifications given in Table III.

TABLE III

PREREGULATOR CHARACTERISTICS

Manufacturer	Beckman (Helipot Division)
Model Number	828
Input Voltage	20 VDC
Output Current (Rated)	1000 mA (Max.)
Output Voltage (V_1)	15 $\pm$0.5%
Ripple Attenuation	180:1
Regulation	
Line	0.0015 (Max.)
Load (No load to 500 mA)	0.01%V_1
Temperature Coefficient	$\pm$100 PPM/^{o}C (Max.)
Stability	$\pm$0.5%/1000 hrs.
Noise	0.005%

The function of the preregulator is to provide a stable input voltage for the zener regulator circuit.

(C) Zener Regulator: The heart of the zener voltage-reference is shown in the 3rd block of Figure 1. The zener regulator is composed of resistor R_1 and zener diode CR_1. The resistor characteristics are shown in Table IV.

TABLE IV

RESISTOR R_1 CHARACTERISTICS

Manufacturer	Vishay
Type	S102 Metal Film
Resistance	799 Ohms
Power Rating	0.3 Watts (125°C)
Temperature Coefficient	± 2 PPM/°C
Stability	± 5 PPM/1000 Hrs.

The preregulator and R_1 form a voltage-resistor current generator as depicted in Figure 2. The value of R_1 is selected to provide the exact bias current required by CR_1.

CR_1 is a temperature compensated zener diode. Its characteristics are stated in Table V.

TABLE V

ZENER DIODE CHARACTERISTICS

Type	1N940B
Voltage (V_3)	9 $\pm 5\%$ VDC
Temperature Coefficient	± 2 PPM/°C (Max.)
Zener Impedance (R_2 Figure 4)	20 Ohms (Max.)
Bias Current (I_2)	7.5 mA
Stability	Not Specified
Noise	Not Specified

The function of CR_1 is to provide additional regulation of the input voltage and form the basis of the reference output.

(D) Load Resistor R_3: The output load is simulated with a fixed resistor of the same type as R_1 (Table IV above). A value of 10^6 ohms was selected for R_3 since this value represents a load typical to that in the aircraft application mentioned in the introduction.

III. CIRCUIT ANALYSIS AND PERFORMANCE PREDICTION

The circuit performance prediction is based on the calculation of the output sensitivity to changes in input voltage, temperature, and time.

Before proceeding to the sensitivity equations, the equivalent circuit for CR_1, the zener diode in Figure 1, must be justified. For the linear region of the V_3 - I_2 characteristic in Figure 3

$$V_3 = \frac{\Delta V_3 \, I_2}{\Delta I_2} + V_2 \qquad (1)$$

where V_2 is a constant determined by the zener diode.

Let

$$\frac{\Delta V_3}{\Delta I_2} = R_2 \qquad (2)$$

The equivalent circuit will hold for small changes of I_2 about the design current [4] . The design current is specified by the manufacturer for minimum temperature coefficient.

A summary list of sensitivity equations is given below (equations (3) through (8)).

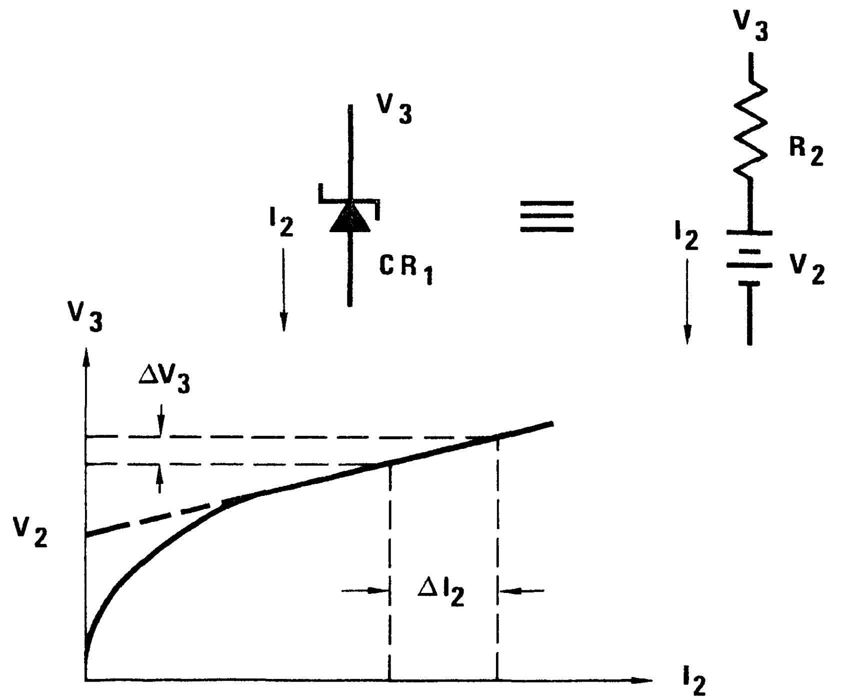
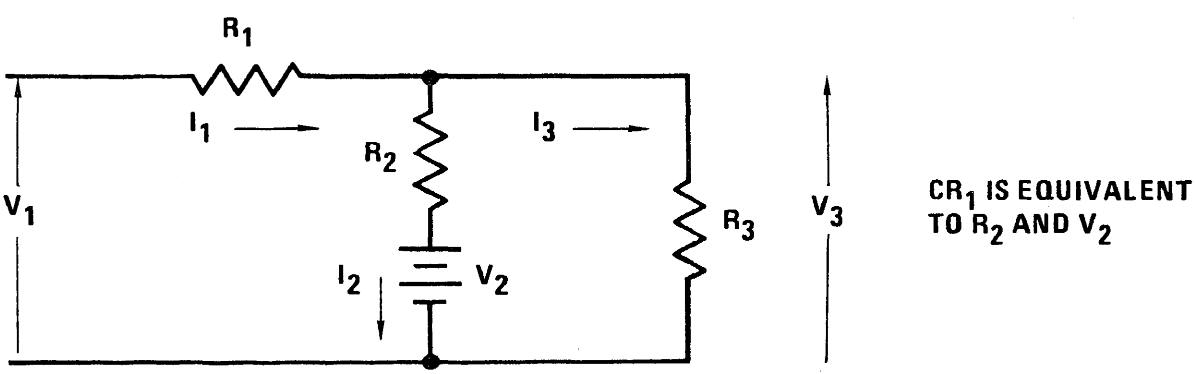


FIGURE 3. ZENER EQUIVALENT JUSTIFICATION



$$V_3 = \frac{V_1 R_2 R_3 + V_2 R_1 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

FIGURE 4. HEART OF THE ZENER REFERENCE CIRCUIT

DESIGN EQUATIONS

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_5'} = \frac{A_1 A_2 A_3 \Delta V_5}{V_3} \tag{3}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_1} = \frac{R_2 \Delta V_1}{V_1 R_2 + V_2 R_1} \tag{4}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{T} = \pm\left[(K_1 V_1 A_3 + K_4 V_4 A_2 A_3)\frac{\Delta T_A}{V_3} + K_2 R_1\left(\frac{\partial V_3}{\partial R_1}\right)\frac{\Delta T_A}{V_3} + K_3 \Delta T_Z\right] \tag{5}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{R_1} = \left(\frac{V_2}{V_1 R_2 + V_2 R_1} - \frac{R_2 + R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}\right) \Delta R_1 \tag{6}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{R_2} = \left(\frac{V_1}{V_1 R_2 + V_2 R_1} - \frac{R_1 + R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}\right) \Delta R_2 \tag{7}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{I_1} = \left(\frac{R_2}{V_2 + I_1 R_2}\right) \Delta I_1 \tag{8}$$

Figure 4 depicts the equivalent circuit for the heart of the reference circuit.

The sensitivities of the output voltage, V_3, to the various circuit elements were determined by familiar methods of the calculus:

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_1} \cong \frac{\partial V_3}{\partial V_1}\,\frac{\Delta V_1}{V_3} \tag{9}$$

where $\left.\frac{\Delta V_3}{V_3}\right|_{V_1}$ is read $\frac{\Delta V_3}{V_3}$ due to V_1.

$\frac{\partial V_3}{\partial V_1}$ is the partial derivative of V_3 with respect to V_1. For derivations of the sensitivity equations, please refer to Appendix A.

In equations (3) through (8) the following definitions apply:

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_5}$$ = the ratio of the change in V_3 to V_3 due to a change in V_5.

$$A_1 = \frac{\Delta V_4}{\Delta V_5} \tag{10}$$ = the ratio of the incremental change in V_4 to the incremental change in V_5.

$$A_2 = \frac{\Delta V_1}{\Delta V_4} \tag{11}$$

$$A_3 = \frac{\Delta V_3}{\Delta V_1} \cong \frac{\partial V_3}{\partial V_1} = \frac{R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \cong \frac{1}{1 + R_1/R_2} \text{ FOR } R_3 \gg R_1 \tag{12}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_1} \cong \frac{\partial V_3}{\partial V_1} \frac{\Delta V_1}{V_3} \cong A_3 \frac{\Delta V_1}{V_3} \tag{13}$$

$$K_1 = \frac{\Delta V_1}{V_1 \Delta T_A} \tag{14}$$ = the temperature coefficient of the preregulator.

$$K_2 = \frac{\Delta R_1}{R_1 \Delta T_A} \tag{15}$$ = the temperature coefficient of resistor R_1.

$$K_3 = \frac{\Delta V_3}{V_3 \Delta T_Z} \tag{16}$$ = the temperature coefficient of the reference diode.

$$K_4 = \frac{\Delta V_4}{V_4 \Delta T_A} \tag{17}$$ = the temperature coefficient of the isolator.

ΔT_A = the incremental change in ambient temperature.

ΔT_Z = the incremental change in the reference diode temperature.

Analysis of the sensitivity equations shows some of the values to control for a stable output voltage. The change in V_3 will be small for:

(1) Small A_1, A_2, A_3, and ΔV_5 (by equation (3)).

(2) Large ratio of R_1 to R_2 (by equation (4)).

(3) Small K_1, K_2, K_3, K_4, $\Delta T_A, \Delta T_Z$ or a selection of polarity and magnitude on the K's to provide compensation of one element against the other (by equation (5)). Temperature coefficient selection is a time consuming job, but where low drift with temperature is important the price may very well be worth it.

(4) Small ΔR_1 (by equation (6)).

(5) Small ΔR_2 (by equation (7)).

(6) Small ΔI_2 (by equation (8)).

The time stability will depend on the time stability of the zener diode and those of the preregulator and the isolator working through their respective sensitivities.

Zener noise, drift with time, and warm-up time are not calculable. Some manufacturers specify drift with time; stabilities of $\pm$ 10 PPM/1000 hours are guaranteed. The values in Table VI for time stability and noise are estimated (where component data are not available). The estimates are based on laboratory measurements of six 1N940B diodes and results of other investigators [1,2,3,6,7].

Table VI below shows the results of calculations of the performance predictions. The calculations are made using the sensitivity equations and the component specifications listed in section II; for details refer to appendix D.

TABLE VI

REFERENCE PERFORMANCE PREDICTIONS

PARAMETER	PREDICTED VALUE	UNITS	EQUATION
$\frac{\Delta V_3}{V_3}$ Versus			
Input Voltage	+0.15	PPM/Volt	(3)
Temperature	$\pm$6.084	PPM/°C	(5)
Time	$\pm$228.9	PPM/1000 hrs	
Noise (Peak-to-Peak)	55.1	PPM	

IV. MEASUREMENT TECHNIQUES AND RESULTS

A laboratory model of the reference circuit was constructed and measurements were made to check the values predicted in section III.

(A) $\frac{\Delta V_3}{V_3}$ VERSUS INPUT VOLTAGE MEASUREMENT:

The measurement circuit is shown in Figure 6 and the results in Table VII.

TABLE VII

OUTPUT VOLTAGE Vs INPUT VOLTAGE TEST DATA

V_5 (VDC)	V_3 (VDC)
25	9.095140
28	9.095150
31	9.095160

Then $$\frac{\Delta V_3}{V_3} = \frac{0.000020}{9.095150} = 2.1989 \times 10^{-6} \quad (18)$$

But $\Delta V_5 = 6$ VOLTS therefore (19)

$$\frac{2.1989 \times 10^{-6}}{6} = 0.366 \times 10^{-6} = 0.366 \text{ PPM/VOLT} \quad (20)$$

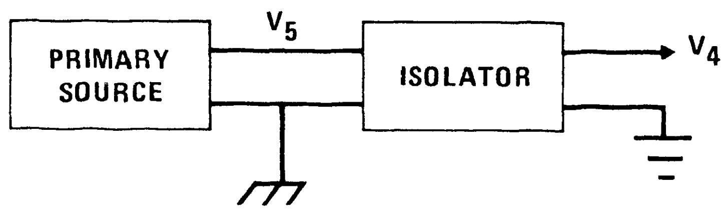


FIGURE 5. PRIMARY CIRCUIT BLOCK DIAGRAM

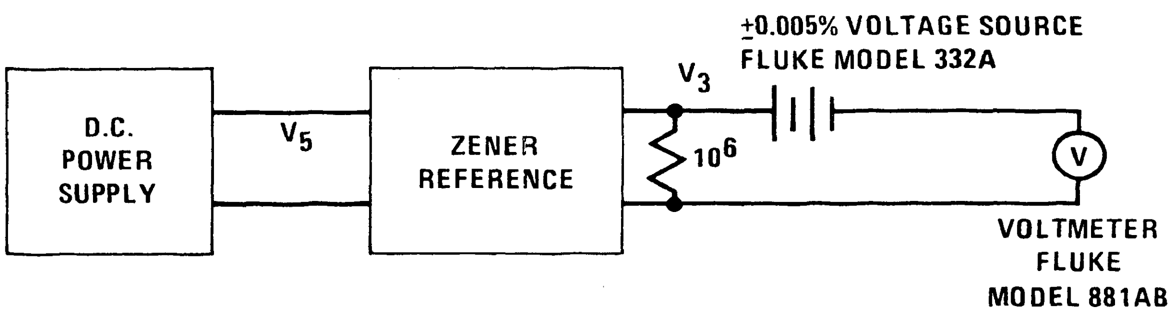


FIGURE 6. OUTPUT VOLTAGE MEASUREMENT SYSTEM

(B) $\frac{\Delta V_3}{V_3}$ VERSUS TEMPERATURE MEASUREMENT:

The same arrangement as shown in Figure 6 was used where V_5 was held at 28 $\pm$0.010 VDC. The zener reference circuit, less R_3, was placed in a thermostatically controlled oven. Results are given in Table VIII.

TABLE VIII

TEMPERATURE TEST DATA

T_A (oC)	V_3 (VDC)	V_1 (VDC)	V_4 (VDC)
27.8	9.096320	15.0472	20.0594
-51.7	9.094660	14.9607	19.9041
-30	9.094510	14.9651	19.8623
- 3.9	9.095310	15.0031	19.9626
15.6	9.096000	15.0336	20.0213
65.6	9.097310	15.0956	20.1430
70	9.098480	15.1425	20.2469

The measurements indicate a low output temperature coefficient between -51.7 and -30°C (-0.76 PPM/°C); between -30 and 65.6°C the T.C. is +3.11 PPM/°C; and between 65.6 and 70°C the T.C. is 5.7 PPM/°C.

(c) $\frac{\Delta V_3}{V_3}$ VERSUS TIME MEASUREMENT:

The voltages V_4, V_1, and V_3 were measured using the comparison technique shown in Figure 6. The results are given in Table IX.

TABLE IX

STABILITY DATA (FIGURE 1 CIRCUIT)

Date	V_3	V_1	V_4
2/13/71	9.095210	15.0441	20.0566
2/20/71	9.095310	15.0430	20.0135
2/27/71	9.095330		
3/6/71	9.096320	15.0472	20.0594
3/12/71	9.096370	15.0494	20.0789
3/18/71	9.096310	15.0474	20.0764
5/21/71	9.095930	15.0482	20.0791
7/9/71	9.096160	15.0186	19.9423

Then $$\frac{\Delta V_3}{V_3} = \frac{9.096370 - 9.095210}{9.095210} = +128 \text{ PPM} \tag{21}$$

for the first 648 hours (2/13/71 to 3/12/71) of operation. Assuming linear drift this corresponds to 198 PPM/1000 hours. The data from 3/12/71 to 5/21/71 show a somewhat lower drift with time:

$$\frac{\Delta V_3}{V_3} = \frac{9.095930 - 9.096370}{9.096370} = -48.4 \text{ PPM} \tag{22}$$

For the period from 5/21/71 to 7/9/71 the drift is:

$$\frac{\Delta V_3}{V_3} = \frac{9.096160 - 9.095930}{9.095930} = 25.3 \text{ PPM} \tag{23}$$

(D) REFERENCE CIRCUIT NOISE MEASUREMENTS:

The output noise of the reference circuit was measured using a Tektronix Model 502A oscilloscope. The peak-to-peak value, as estimated from the oscilloscope reading, was 500 microvolts (55.5 PPM). The waveform of the noise is shown in Figure 12.

Figure 11 shows the zener noise as a function of bias current. The isolator noise output was 0.01 volts peak-to-peak by the above method.

(E) SHORT CIRCUIT MEASUREMENTS:

The output voltage measurement system of Figure 6 was used in the short circuit test. The voltage source (Fluke Model 332A) and voltmeter circuit was removed and a short was applied to the reference output.

OUTPUT SHORT CIRCUIT TEST DATA:

V_3 prior to short circuit = 9.095810 VDC.

V_3 after a 5 second short circuit = 9.095860 VDC.

V_3 recovers to 9.095830 VDC within 10 seconds.

The power rating of R_1 must be selected to withstand the output short circuit condition. This value is 0.28 watts (15 volts across 800 ohms).

(F) RESISTOR R_1 TEMPERATURE MEASUREMENT:

The data of Table X were obtained.

TABLE X

RESISTOR R_1 TEMPERATURE DATA

Temperature (°C)	R_1 (Ohms)
25	799.085
97.8	799.025

Since $\Delta T = 72.8^{o}C$ and $\Delta R_1 = -0.060$

then $$\frac{\Delta R_1}{R_1 X \Delta T} = \frac{-0.060}{799.025 \ X \ 72.8} = -1.04 \ X \ 10^{-6} = -1.04 \quad PPM/^{o}C \qquad (24)$$

V. COMPARISON OF PREDICTED AND MEASURED PERFORMANCE

Table XI shows the comparison of predicted values as calculated in section III with measured values as acquired by the methods of section IV.

TABLE XI

COMPARISON OF PREDICTED AND MEASURED PERFORMANCE

PARAMETER	MEASURED VALUE	PREDICTED VALUE	UNITS
$\frac{\Delta V_3}{V_3}$ Vs INPUT VOLTAGE	+0.366	+0.150	PPM/VOLT
TEMPERATURE	-0.76 to +5.7	±6.084	PPM/°C
TIME	+198	±228.9	PPM/1000 hrs.
NOISE (PEAK-TO-PEAK)	55.5	55.1	PPM

The differences between predicted and measured values are discussed in the following section.

VI. DISCUSSION

(A) GENERAL:

The following is a discussion to clarify the discrepancies between the predicted and the measured values shown in Table XI.

As indicated in section III, the change in output due to change in supply voltage should be 0.150 PPM/Volt. The measured value was 0.366. The isolator line regulation, A_1, was 37 times lower than specified by the manufacturer and the preregulator line regulation was 110 times higher, and the zener circuit was 1.275 times lower than the value used in the performance prediction. These three factors account for the difference between the measured value, 0.366, and the calculated value, 0.150.

The output change for a change in temperature is predicted based on the assumption that the circuit elements have constant temperature coefficients. Plots of the data of Table VIII reveal nonlinear temperature coefficients (see Figure 7 below). The range of output temperature coefficients is indicated on the curve of V_3 versus temperature.

The plots of the temperature data for the isolator voltage and preregulator voltage are similar in shape to that of the reference output suggesting that all or part of the output change with temperature may be due to the change in V_1 and V_4. (The performance prediction, calculated in Appendix D, indicates that the major contributors to the temperature error will be the preregulator and the zener diode.) The measurement data for the laboratory model from Table D-1 inserted into the performance prediction equations indicate a value of +2.314 PPM/°C for the overall temperature coefficient; this compares favorably with the measured value of 3.11 PPM/°C between -30 and +65°C.

The preregulator output variation with temperature is a function of its temperature coefficient and the change in the isolator voltage with temperature. The apparent temperature coefficient of the preregulator is +60 PPM/°C as derived from the measurement data (Table VIII). The preregulator temperature coefficient is also a nonlinear function. The value of +60 PPM/°C is approximately true for the temperature range of -30°C to +65°C.

The zener diode temperature coefficient was determined prior to its insertion into the circuit of Figure 1. Six diodes were tested for temperature coefficient. The data summary is shown in Table XII.

TABLE XII

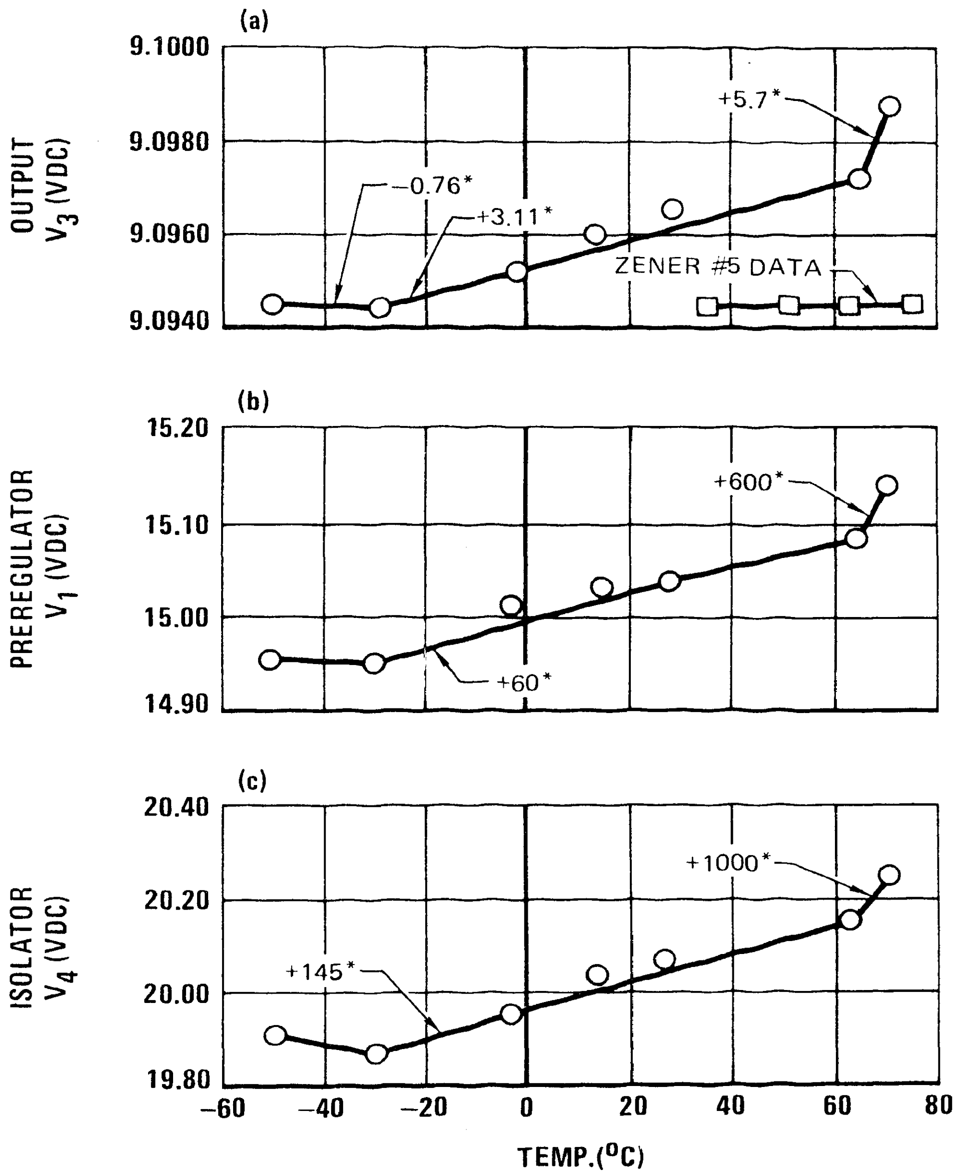
TEMPERATURE DATA SUMMARY FOR 6 1N940B DIODES

DIODE	TEMPERATURE COEFFICIENT		NOISE (μV)	
#	%/°C	PPM/°C	30.6°C	84.4°C
1	-0.0015	-15	400	360
2	+0.0025	+25	1290	1475
3	-0.00022	-2.2	565	650
4	-0.0011	-11	480	460
5	-0.00005	-0.5	445	520
6	-0.00085	-8.5	890	780

The data, from which the above summary was obtained, appear in Appendix C.

Zener #5 was selected for use in the laboratory model. Its high-temperature characteristic is plotted in Figure 7 (a).

The time stability predicted by the calculations in Appendix D is ±228.9 PPM/1000 hours. The measurement data show a change of the same



*SLOPE IN PPM/^{o}C

FIGURE 7. TEMPERATURE TEST DATA PLOTS

order of magnitude, +198 PPM/1000 hours. It is interesting to examine the stability data in detail. Plotting the data and drawing a best straight line through the data points (Figure 8), shows that the lines all have a positive slope (suggesting that the change in output, ΔV_3, may be a result of the change in V_1). To show that the change in the output is due primarily to the zener, the following calculation is made:

For the 30 day period (2/13/71 to 4/15/71):

$$\frac{\Delta V_3}{V_3} = \frac{A_3 \Delta V_1}{V_3} \tag{25}$$

$$= \frac{(0.019)\,(0.0063)}{9.09} = 13.2 \times 10^{-6} = 13.2 \text{ PPM/30 DAYS} \tag{26}$$

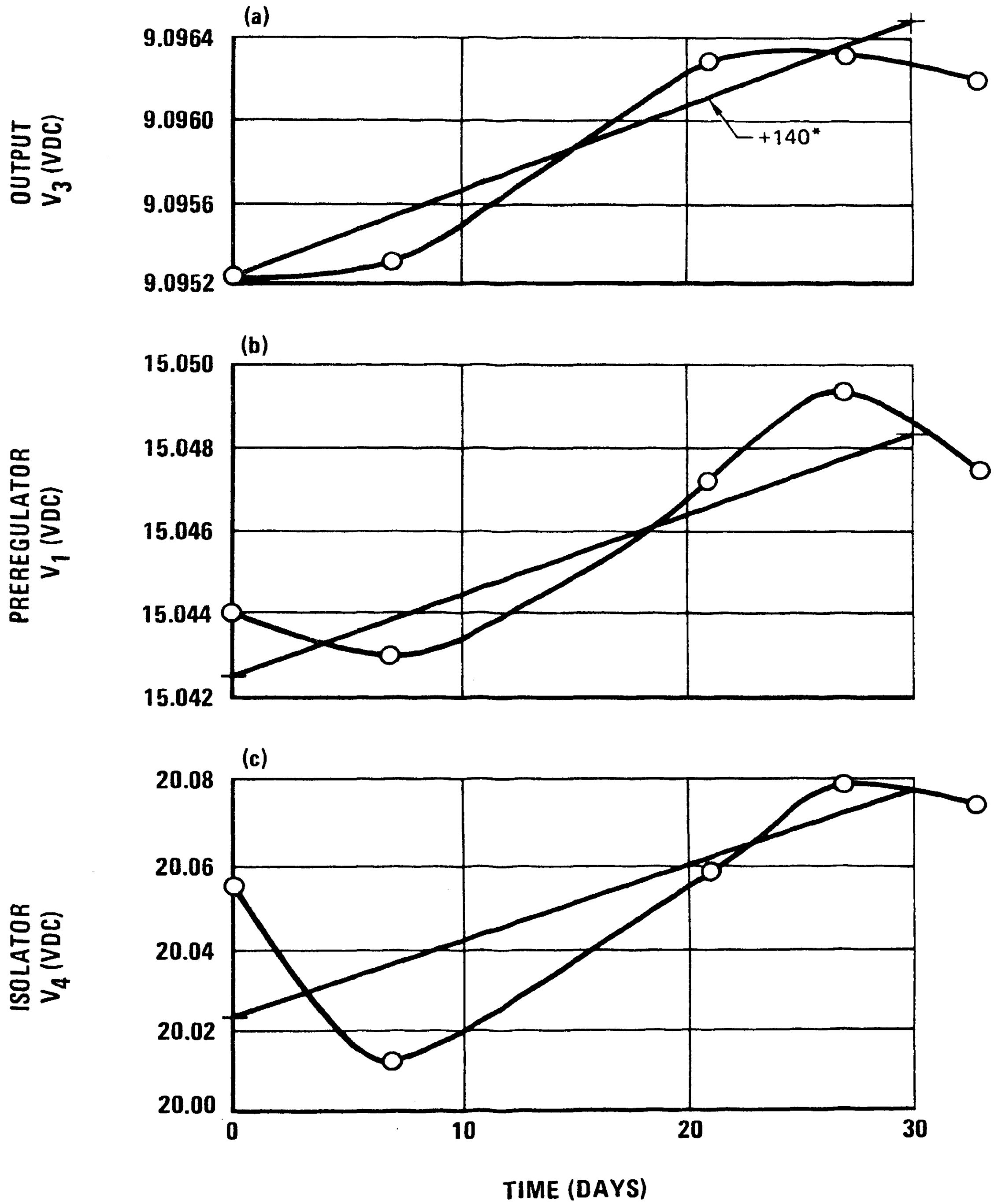
where the value of ΔV_1 is read from the best straight line in Figure 8 (b) for a 30 day interval.

The measured output change is:

$$\frac{\Delta V_3}{V_3} = \frac{0.001270}{9.09} = +140 \times 10^{-6} = 140 \text{ PPM/30 DAYS} \tag{27}$$

where ΔV_3 is taken from the best straight line in Figure 8 (a). Therefore, 126.8 PPM/30 days is attributed to the zener diode and/or the resistor R_1. This is much more than the value predicted for the zener alone, ±25 PPM/1000 hours. (126.8 PPM/30 days is 194 PPM/1000 hours).

Prior to fabrication, six 1N940B diodes were subjected to stability measurements. The results of these measurements are at odds with the measurements on the completed circuit. The measurement system shown in



*SLOPE OF BEST STRAIGHT LINE PPM/30 DAYS

FIGURE 8. STABILITY TEST DATA PLOTS

Figure 9 was used to acquire the time stability data. The diode voltage readings and time histories are included in Appendix B. A data summary follows in Table XIII.

TABLE XIII

STABILITY DATA SUMMARY FOR 6 1N940B DIODES

ZENER #	FINAL SLOPE	
	μV/1000 hrs.	PPM/1000 hrs
1	-150	-17
2	-250	-28
3	+250	+28
4	-1750	-195
5	0	0
6	-350	-39

Final slope refers to the expected rate of change in zener voltage with time following a 10 day aging period.

The tests indicate higher drift rates in the early phase of the aging period. (See diodes 1, 2, 4, and 6 Appendix B). The overall drift pattern follows that of other investigators of compensated zener reference diode stability [1]. That is, some diodes drift up in voltage, others drift down. Some drift linearly from turn-on, others drift rapidly at first then taper off. The drift of #5 was not measurable.

For a stable voltage-reference, it is advisable to pre-age all diodes, i.e., operate at rated current for no less than 20 days.

Zener #5 was selected for use in the laboratory model since its temperature coefficient was low and its stability high. Since it is

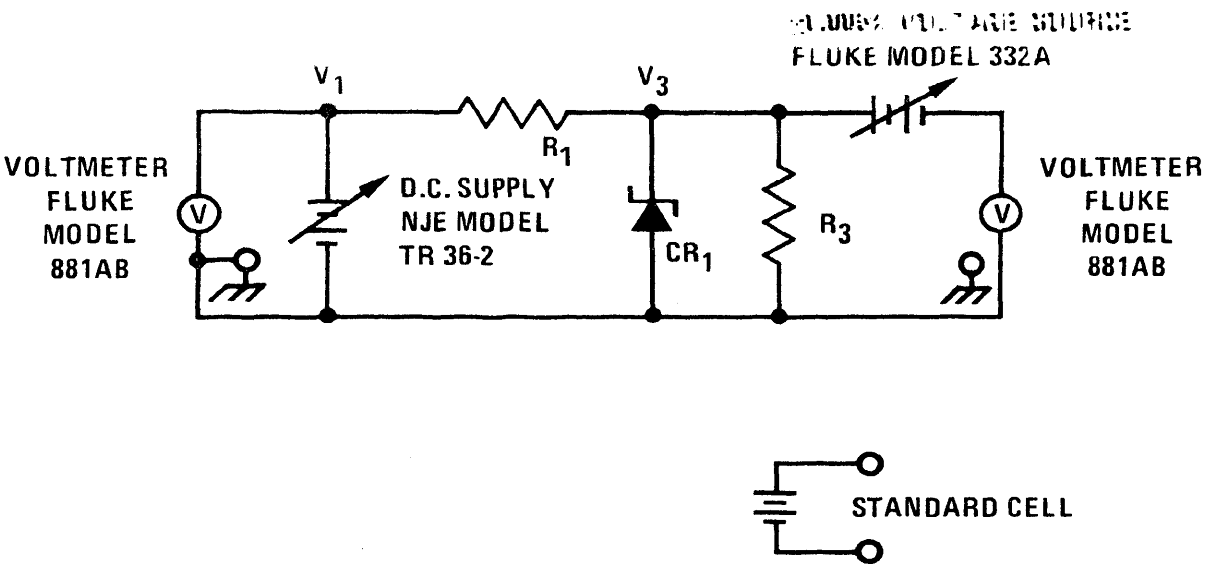


FIGURE 9. MEASUREMENT CIRCUIT FOR STABILITY TESTS

unlikely that the resistor, R_1, aged enough to cause the output change recorded in Table IX, it is assumed that the drift characteristic of the zener diode changed as a result of its insertion into the final circuit.

The circuit noise measurement agrees fairly well with the predicted value since the predicted value was based on measurement of the zener noise (the largest contributor). The fact that the total circuit noise exceeds the zener noise by only 0.5 PPM suggests that the contributions due to the preregulator and isolator are smaller than that predicted. Subsequent measurements of isolator output noise confirm this. Noise measurements were made using a true rms voltmeter and medium-bandwidth oscilloscope (DC to 500 KHZ). The measurement circuit is depicted in Figure 10. The measurements were carried out inside a screen room, but this precaution was not necessary in view of the amount of noise generated by the diode as compared to that induced by external sources. The true rms value was 280 microvolts while the peak-to-peak value, as estimated from the oscilloscope reading, was 500 microvolts for diode #5.

The noise data are recorded in Appendix C and is summarized in Table XII.

(B) IMPROVEMENTS:

The most obvious improvement, based on predicted performance, should be found in the area of time stability. When applying the voltage-reference, one would rather not have to reset circuit values to maintain the bias current in the zener diode (for low zener temperature coefficient) or reset the output voltage. This means that a stable preregulator is required. It is most likely that the stability of the preregulator is

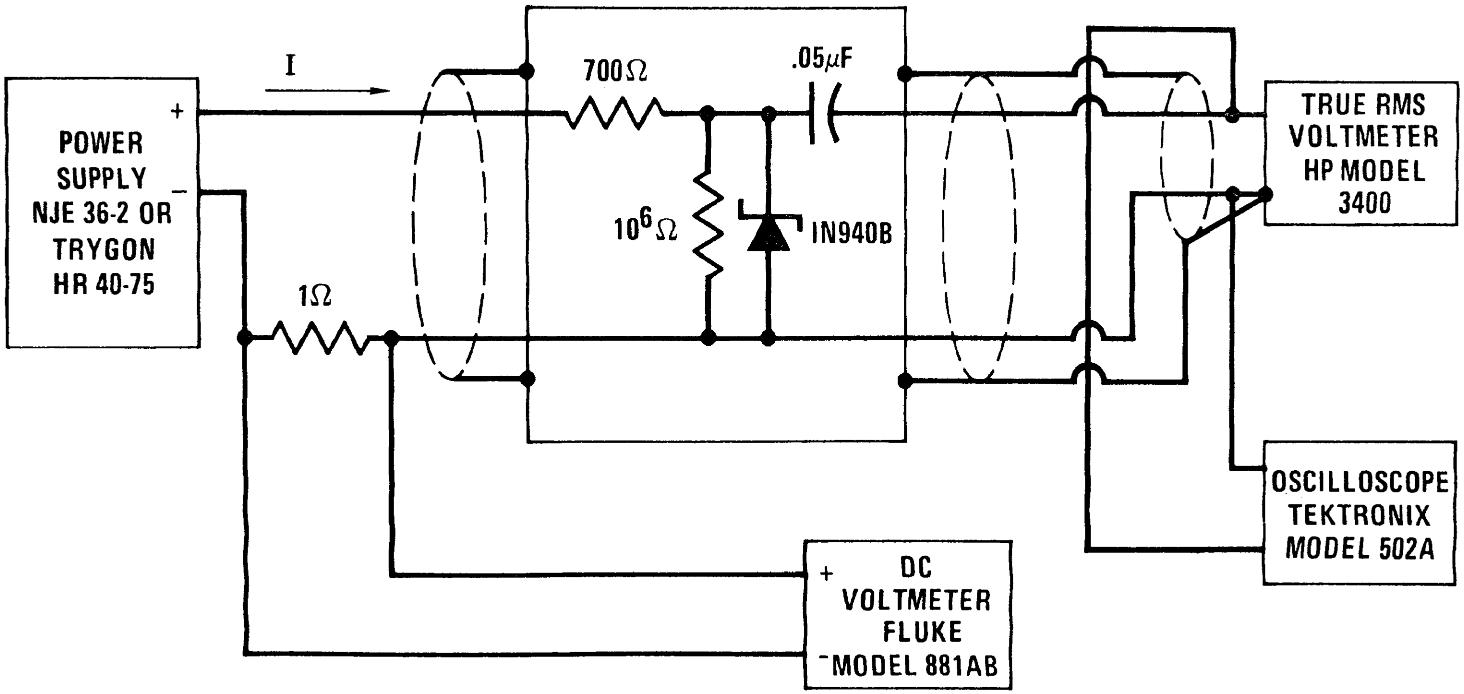


FIGURE 10. ZENER DIODE NOISE MEASUREMENT CIRCUIT

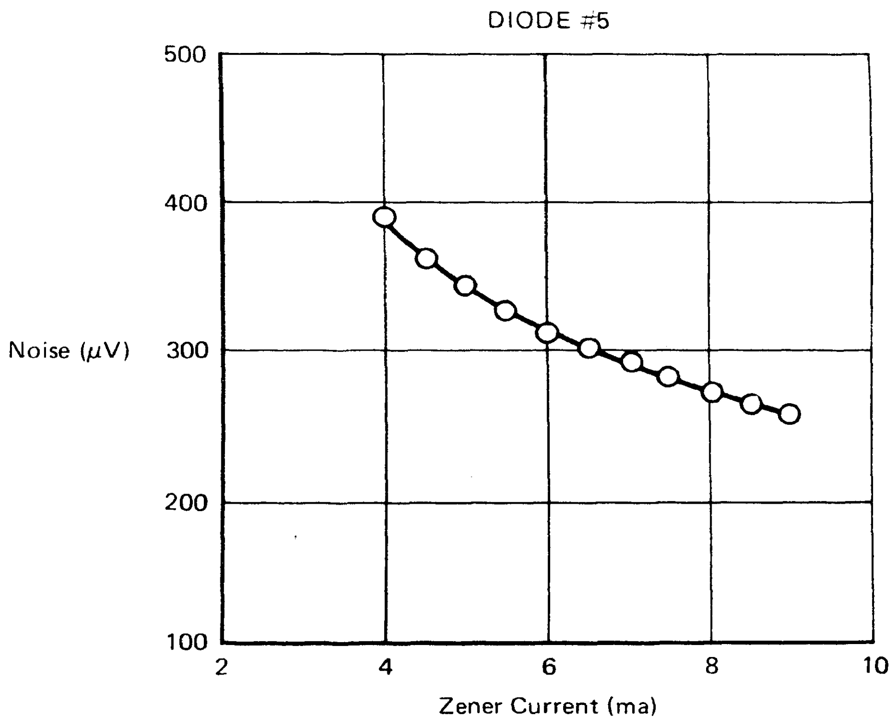


FIGURE 11. ZENER NOISE vs BIAS CURRENT (IN940B)

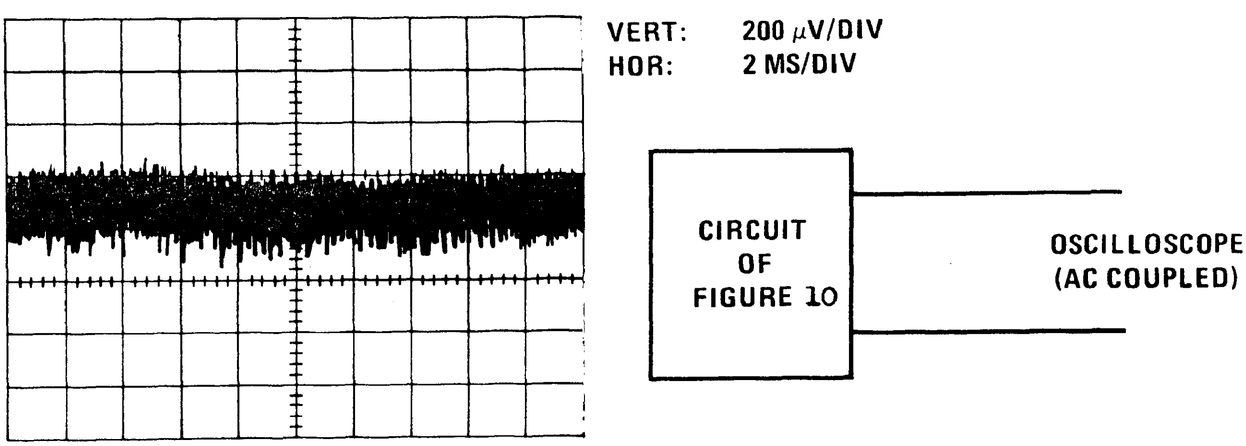


FIGURE 12. ZENER NOISE WAVEFORM (IN940B)

a function of a zener diode reference within the preregulator. Therefore, it is not unreasonable to expect that the preregulator stability could be as good as 25 parts per million per 1000 hours. (This value should be compared with the value of 5000 parts per million per 1000 hours specified for the unit used in the laboratory tests).

The laboratory model tests show a stability of 2200 PPM/1000 hrs. for one such preregulator. The drift in V_1 due to V_4 has been subtracted.

The second area of improvement would be reduction of the output noise. As can be seen from the oscilloscope trace, Figure 12, the peak-to-peak output noise exceeds 400 microvolts. In general, some portion of the 9 volt output would be used in a reference application. To reduce noise, one would use the circuit of Figure 13. The resistance values of R_{3a}, R_{3b}, and R_{3c} equal the value of R_3 in Figure 1.

Using the condition

$$R_{3_a} = R_{3_b} \tag{28}$$

the output voltage is

$$V_o = V_3 \frac{R_{3_c}}{10^6} \tag{29}$$

C_1 is a low-leakage capacitor that forms a low-pass filter with R_{3a}, R_{3b}, and R_{3c}. The filter cutoff frequency is

$$f_c = \frac{1}{2\pi R C_1} \tag{30}$$

where

$$R = \frac{R_{3a}(R_{3b} + R_{3c})}{10^6}. \tag{31}$$

and the internal resistance of the zener circuit is negligible.

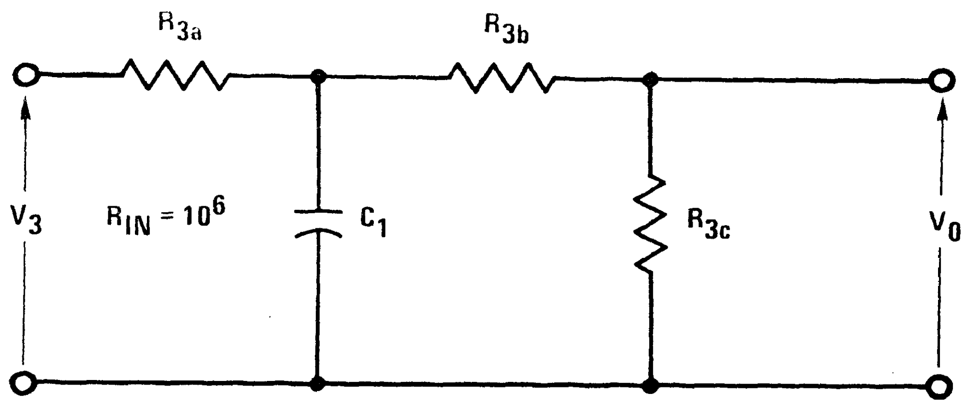


FIGURE 13. FILTERED OUTPUT CIRCUIT

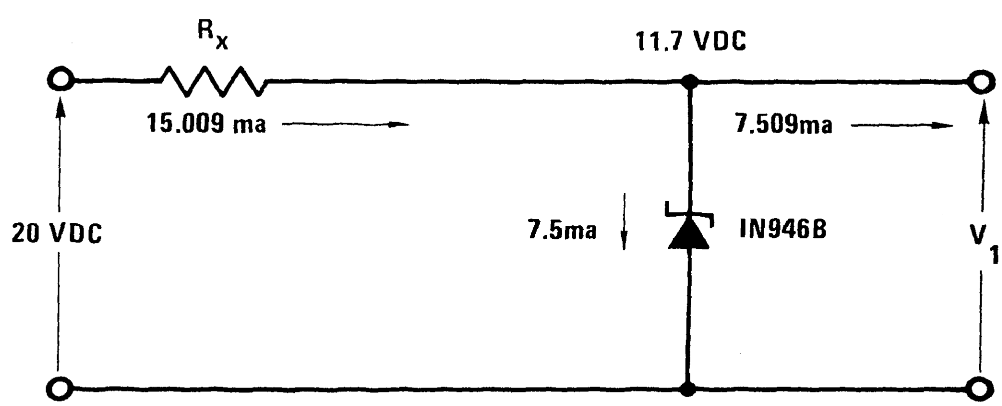


FIGURE 14. ALTERNATE PREREGULATOR CIRCUIT

The added resistors and capacitor will cause additional time and temperature errors in the output as well as make the circuit more load sensitive but noise can be reduced significantly.

The third area of improvement is reduction of the output temperature coefficient. Two methods will be described.

Method (1): Choose a preregulator with a low temperature coefficient. One such preregulator is shown in Figure 14.

The series resistance is

$$R_x = \frac{(20-11.7)\ 10^3}{15.009} = 550 \text{ ohms} \tag{32}$$

R_1 (Figure 1) must be reduced to 360 ohms; this in turn increases the output sensitivity to changes in V_1.

The preregulator line regulation, A_2, is 0.048. This is 32 times larger than the specified value of the preregulator described in Table III and must be considered in the overall design.

The temperature coefficient of the preregulator shown in Figure 14 is ± 2 PPM/°C which is considerably better than the ± 100 PPM/°C value stated in Table III.

As was stated earlier, the time stability of this preregulator is expected to be much better than the preregulator described in Table III. The noise is also expected to be much greater than that specified in Table III.

Method (2): Isolate the temperature sensitive elements from the temperature change. The method used to isolate standard cells from temperature changes is to surround them by some sort of controlled environment [8]. The same sort of thing can be done for reduction of the zener contribution to the reference output variation with temperature. There are small self-regulating component ovens available (e.g., KLIXON manufactured by Texas Instruments, Inc.). These ovens will reduce the temperature variation about the diode by a factor of 1/15 or more. The ovens require an external power source for operation. They are non-voltage sensitive, unaffected by component current, radio noise-free, and free from moving parts.

Other areas of improvement involve taking advantage of the information contained in the sensitivity equations. It can be seen that it is profitable to reduce $\left.\frac{\Delta V_3}{V_3}\right|_{V_1}$ by increasing V_1 (up to a point).

$$\lim_{V_1 \to \infty} \left.\frac{\Delta V_3}{V_3}\right|_{V_1} = \frac{K R_2 I_2}{V_3} \qquad (33)$$

$$\text{WHERE } K = \frac{\Delta V_1}{V_1}. \qquad (34)$$

Then R_1 is increased as V_1 is increased to keep I_2 constant at the design bias current.

A plot of $\left.\frac{\Delta V_3}{V_3}\right|_{V_1}$ vs V_1 shows that $\left.\frac{\Delta V_3}{V_3}\right|_{V_1}$ approaches the value in equation (33) asymptotically. There is little advantage in going beyond 30 volts for V_1 using the voltages of the circuit in Figure 1.

(C) AREAS FOR FUTURE STUDY:

One of the recommendations of this paper is that diodes be selected with low time and temperature drifts. Some quick and easy way is required to select the diodes. It was reported [6] that correlation exists between zener noise output and long term stability. In another investigation [7] no such correlation was found for the temperature compensated diodes of the type used in this paper. The randomness of the time stability curves casts a doubt as to the possibility of finding a quick selection method. Manufacturing process cleanliness may be a factor in producing stable diodes [7] .

A second area for future study is the determination of zener diode aging characteristics with intermittent power application. Eicke [7] suggests that diodes kept under power will exhibit a more stable output than those subjected to intermittent power.

A third area of study involves temperature cycling. The questions to be answered are: 1) Does stability improve by maintaining the diodes at constant temperature? 2) Does stability improve by choosing a high temperature (+85°C) or a low temperature (-55°C)? 3) With regard to aging, should the diodes be aged under power? 4) Does high temperature accelerate the aging?

A fourth area is the determination of noise characteristics. The questions here are: 1) What causes the noise generated by zener diodes? 2) What effect does externally generated noise have on temperature and stability characteristics? Not enough work has been reported on the characterization of zener diode noise.

VII. CONCLUSION

Some of the more important factors in the design of a zener reference circuit have come to light as a result of analyisis and measurement of a particular circuit. With judicious choice of circuit components, a very stable voltage-reference may be obtained using a zener diode as the reference element.

Two of the three major sources of error (deviation from a constant voltage traceable to the national standard) are predictable and controllable; these are changes due to input voltage, where a voltage-resistance current source is used, and changes due to temperature. The third, changes due to time (component value drift) may be calibrated out by periodic checks against voltage standards.

Peak-to-peak noise generated by the zener diode can run upwards of 1000 microvolts. The noise can be filtered out depending on the reference application.

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X. REVIEW OF LITERATURE

The design of zener diode reference circuits is covered in many books and articles. The topics and procedures in this paper are not shown explicitly in any of the references, section VIII, or any of the items of the bibliography, section IX.

Several items listed in sections VIII and IX are described below to show some of the approaches and results.

"A Theory of the Electrical Breakdown of Solid Dielectrics," a paper by Clarence Zener, develops the theory that direct excitation of electrons by an electric field causes the electrical breakdown of solid dielectrics. The magnitude and the suddeness with which the breakdown occurs are predicted and then verified by measurements.

"Analysis of Voltage-Regulator Operation," by W.R. Hill, shows that the performance of any regulator circuit can be analyzed in terms of two parameters defined as the internal resistance and the regulation factor. Typical regulator circuits are analyzed to evaluate the two parameters and to show the effects of circuit changes in improving regulator performance.

"Silicon P-N Junction Alloy Diodes," by G.L. Pearson and B. Sawyer, describes a type of P-N junction diode prepared by alloying acceptor or donor impurities with N- or P-type silicon. Among other properties, the diodes have a d(log I)/d(log V) (zener characteristic) as high as 1500 over several decades of current. Production processes are defined for stable zener voltages between 3 and 1000 volts.

"The Suitability of the Silicon-Alloy Junction Diode as a Reference Standard in Regulated Metallic Rectifier Circuits," by D.H. Smith, discusses the suitability of silicon-alloy junction diodes having very sharp reverse breakdown characteristics in the reference standard portion of closed-loop feedback regulating circuits of metallic rectifiers. The paper shows the decreased use of vacuum-tube and magnetic-amplifier regulating circuits.

"Current Reference for Magnetic Amplifiers," by D.A. Burt, is a how-to-design paper showing the zener diode equivalent circuit as a battery and a resistor. The paper contends that the ratio of the battery voltage to the resistance should be as large as possible for reference use. The paper shows how to calculate a temperature sensitive resistance which will compensate the circuit for variations in temperature; a circuit's performance is predicted and measurements are taken which show agreement with the theory.

"Diffused Silicon Diodes--Design, Characteristics, and Aging Data," by H.E. Hughes, describes the design of high reliability diodes by the diffusion process. The process stresses vacuum tight sealing, no fluxes or metallic flash in contact with the semiconductor, and chemical cleanliness of the interior of the unit.

"Eigenschaften Von Zener-Dioden Und Ihre Anwendung Als Spannungsnormal," by F. Meyer-Broetz, describes the application of zener diodes as voltage standards; they are especially suited as voltage standards in transistorized equipment. Their advantages include long life, small dimensions, and high shock resistance.

"A Low Voltage Stabilizer Employing Junction Transistors and a Silicon Junction Reference Diode," by D. Aspinall, shows a zener diode used as a reference source in a series voltage stabilizer. Approximate equations for the output impedance and stabilizing factor are presented and checked experimentally.

"Broadband Radio Interference Generated by Airborne Electronic Devices Utilizing Diode Rectifiers," by J.L. Senn, points out that semiconductor diodes can generate serious radio frequency interference under certain conditions. The work covered in the paper includes the investigation of the cause of differences in interference generation among otherwise identical junction diodes.

"High Voltage Transistor Regulated Supplies," by Michel Mamon, is a circuit analysis and a step-by-step design procedure for transis tor regulated supplies. Temperature effects on the zener reference are included.

"Designing for Zeners," by Alan Ross, discusses the theory and design of shunt regulators. A method is shown to allow selection of the optimum zener diode for a given set of input and load conditions.

"Designing Zener Diode Voltage Regulators," by R.G. McKenna, gives design curves and equations. The use of the curves and equations is shown for typical zener diode voltage regulators.

"An Ultra Stable Diffused Subminiature Voltage Reference Diode," by Windsor Hunter, describes the development of a diode reference combining a zener diode with a compensating forward biased diode (formed simultaneously by diffusion). Stability of the diodes is adequate for many standard cell applications.

<u>Zener Diode Handbook</u> by J.K. Buchanan and others, is a book covering basic theory, design characteristics and applications for

zener diodes. Among other things, impedance cancellation and testing methods are discussed.

"Zener Diode Switches," by Hubert C. Nichols, Jr., a Master's Thesis, theorizes that zeners switching in the zener mode are 1000 to 10,000 times faster than diodes in the forward conduction region. Tests showed them to be only twice as fast (probably because of test equipment limitations).

"Reference Voltage with Self-Contained Current Source" is an application note from the Dickson Co. describing a zener diode, field-effect transistor (fet) device which eliminates the need for current controlling circuitry. The fet temperature coefficient (TC) compensates for the diode TC providing a stable reference voltage at temperatures from -55°C to 100°C. The change in output for input voltage changes is typically 12.5 PPM/Volt. Applications described include a working source for potentiometers, a standard cell replacement, and a voltage-reference for operational amplifier circuits.

"The Operating Characteristics of Zener Reference Diodes and Their Measurements," by Woodward G. Eicke, Jr., describes a measurement technique which allows stability measurements to an accuracy of 2 to 4 PPM. The stability data for three diodes are shown. Current was maintained through the diodes at all times. A voltage-temperature-current relationship was derived from voltage versus temperature and voltage versus current measurements. The zener voltage shift due to an AC component superimposed on the DC bias was also measured. The zener voltage shift was abrupt for AC above 2 KHz. The noise output was measured and found to vary greatly among different diodes. The author supports the findings of Baker and Nagy that a relationship exists between noise output and stability for alloy-type temperature-compensated diodes. No such correlation was found for diffused-junction diodes.

"Reappraising the Zener Diode as a Reference and Transport Standard," also by Eicke, is an update of the previous paper showing results of the National Bureau of Standard's evaluation of zener diodes. A number of methods to measure zener diode characteristics are described. The voltages of three NBS zener diodes were measured at Boulder and then carried to West Germany and measured; the results agreed within 2 PPM, the uncertainty of the Boulder measurement alone (with respect to the NBS volt). Seven zener reference units (nominal output voltage of 1.017 to 1.018 volts) were compared to saturated standard cells. The zener units exhibited random noise components not present in the standard cells. The zener units also drifted with time all units showing a decrease in voltage with time. The drift is roughly six times that of standard cells. The zener units can be used as a 2-3 PPM transport standard under proper measurement conditions.

"Ultra Stable Reference Elements," appearing in <u>Electronic Industries</u> in 1963, was based on a report by R.N. Minke of Pacific Semiconductors, Inc. It points out that the unsaturated standard cell was the most accurate reference available (for precision DC equipment) until the temperature-compensated zeners came along. Long term stabilities as low as $\pm$ 100 PPM are indicated. The article lists some of the limitations of standard cells and goes on to show how the zener overcomes these.

"Characteristics of Silicon Junction Diodes as Precision Voltage References Devices," by Kurt Enslein, is an early paper that lists several previously published papers on the subject under the heading of "Previous Art." The paper gives measurement data for several uncompensated and compensated diodes. Curves of ΔR, R and $\Delta R/R$ versus zener current are shown as are zener voltage versus temperature. Circuit start-up (ignition) effects are graphed (a time history of the zener voltages versus time is made from turn-on through stabilization). Gaseous reference tubes, standard cells, mercury cells, and zener diodes are compared for short term fluctuations, long term fluctuations, audio noise, life expectancy, ΔR, $\Delta R/R$, and temperature coefficient.

"Standard Cells, Their Construction, Maintenance, and Characteristics," by Walter J. Hamer, gives the origin and derivation of the unit of electromotive force and outlines the procedures by which the NBS maintains and disseminates this unit by means of standard cells. Information is also given on construction and characteristics of standard cells as well as a history of their development. It is interesting to note that the standards maintained in Russia were 23.1 microvolts above the rest of the world until 1950 when an adjustment of 13 microvolts was made. The spread between five other great countries was 3.3 microvolts. The paper discussed effects of load, light, shock, and vibration on cell output.

XI. VITA

Armond Charles Maxeiner was born on November 11, 1930, in St. Louis, Missouri. He received his primary and secondary education in Ferguson, Missouri. He received his college education from Missouri University, in Columbia, Missouri; Washington University, in St. Louis, Missouri; and the University of Missouri-Rolla, St. Louis Extension, St. Louis, Missouri. He received a Bachelor of Science degree in Electrical Engineering from the University of Missouri in June, 1957.

He has been enrolled in the Graduate School of the University of Missouri-Rolla since September 1966. He has been employed at McDonnell Douglas Corporation, St. Louis, since June 1956.

APPENDIX A

DERIVATION OF THE SENSITIVITY EQUATIONS

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_5}$$

$$\text{LET } A_1 = \frac{\Delta V_4}{\Delta V_5}$$

$$\text{LET } A_2 = \frac{\Delta V_1}{\Delta V_4}$$

$$\text{LET } A_3 = \frac{\Delta V_3}{\Delta V_1}$$

$$A_1 \cdot A_2 \cdot A_3 = \frac{\Delta V_4}{\Delta V_5} \cdot \frac{\Delta V_1}{\Delta V_4} \cdot \frac{\Delta V_3}{\Delta V_1} = \frac{\Delta V_3}{\Delta V_5}$$

$$\boxed{\frac{A_1 \cdot A_2 \cdot A_3 \cdot \Delta V_5}{V_3} = \left.\frac{\Delta V_3}{V_3}\right|_{V_5}}$$

A_1, A_2, & A_3 ARE POSITIVE FOR THE CIRCUIT ELEMENTS CHOSEN, I.E., AN INCREASE IN INPUT PRODUCES AN INCREASE IN OUTPUT (VOLTAGE).

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_1} \cong \frac{\partial V_3}{\partial V_1} \frac{\Delta V_1}{V_3}$$

$$V_3 = \frac{V_1 \; R_2 R_3}{D} + \frac{V_2 \; R_1 R_3}{D}$$

$$D = R_1 R_2 + R_1 R_3 + R_2 R_3$$

$$\frac{\partial V_3}{\partial V_1} = \frac{R_2 R_3}{D} \cong \frac{\Delta V_3}{\Delta V_1}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_1} = \frac{R_2 R_3}{D} \cdot \frac{D \, \Delta V_1}{V_1 R_2 R_3 + V_2 R_1 R_3}$$

$$\boxed{\left.\frac{\Delta V_3}{V_3}\right|_{V_1} = + \frac{R_2 \, \Delta V_1}{V_1 R_2 + V_2 R_1}}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_T = \left.\frac{\Delta V_3}{V_3}\right|_{\Delta V_4}\Big|_T + \left.\frac{\Delta V_3}{V_3}\right|_{\Delta V_1}\Big|_T$$

$$+ \left.\frac{\Delta V_3}{V_3}\right|_{\Delta R_1}\Big|_T + \left.\frac{\Delta V_3}{V_3}\right|_{CR_1}\Big|_T$$

WHERE $\left.\frac{\Delta V_3}{V_3}\right|_{\Delta V_4}\Big|_T$ = THE FRACTIONAL CHANGE IN V_3 DUE TO A CHANGE IN V_4 WITH TEMPERATURE, ETC.

LET K_4 = TEMPERATURE COEFFICIENT OF THE ISOLATOR (V_4).

$$\pm K_4 = \frac{\Delta V_4}{V_4 \, \Delta T_A}, \text{ OR } \Delta V_4 = \pm K \, V_4 \, \Delta T_A$$

$$\left.\begin{aligned} A_2 &= \frac{\Delta V_1}{\Delta V_4} \\ A_3 &= \frac{\Delta V_3}{\Delta V_1} \end{aligned}\right\} \frac{\Delta V_3}{\Delta V_4} = A_2 \, A_3$$

$$\frac{A_2 \, A_3 \, \Delta V_4}{V_3} = \frac{\pm A_2 \, A_3 \, K_4 \, V_4 \, \Delta T_A}{V_3} = \left.\frac{\Delta V_3}{V_3}\right|_{\Delta V_4}\Big|_T$$

THE "K's" ARE EITHER POSITIVE OR NEGATIVE SINCE THE VOLTAGE CHANGES FOR AN INCREASE IN TEMPERATURE CAN BE POSITIVE OR NEGATIVE.

LET K_1 = TEMPERATURE COEFFICIENT OF THE PREREGULATOR (V_1).

$$\pm K_1 = \frac{\Delta V_1}{V_1 \, \Delta T_A}, \text{ OR } \Delta V_1 = \pm K_1 \, V_1 \, \Delta T_A$$

$$A_3 = \frac{\Delta V_3}{\Delta V_1}$$

$$\frac{A_3 \, \Delta V_1}{V_3} = \frac{\pm A_3 \, K_1 \, V_1 \, \Delta T_A}{V_3} = \frac{\Delta V_3}{V_3} \bigg|_{\Delta V_1} \bigg|_{T}$$

LET K_2 = TEMPERATURE COEFFICIENT OF R_1.

$$\pm K_2 = \frac{\Delta R_1}{R_1 \, \Delta T_A} \text{ , OR } \Delta R_1 = \pm K_2 \, R_1 \, \Delta T_A$$

$$\frac{\Delta V_3}{V_3} \bigg|_{R_1} \bigg|_{T} = \frac{\pm \partial V_3}{\partial R_1} \; \frac{K_2 \, R_1 \, \Delta T_A}{V_3}$$

WHERE $\pm K_2 \, R_1 \, \Delta T_A = \Delta R_1$

$$\frac{\Delta V_3}{V_3} \bigg|_{R_1} \bigg|_{T} = \frac{\pm K_2 \, R_1}{V_3} \left[\frac{V_2 \, R_3}{D} - \frac{V_1 \, R_2 \, R_3 \, (R_2 + R_3)}{D^2} - \frac{V_2 \, R_1 \, R_3 \, (R_2 + R_3)}{D^2} \right] \Delta T_A$$

WHERE $D = R_1 \, R_2 + R_2 \, R_3 + R_1 \, R_3$

$$\frac{\partial V_3}{\partial R_1} \cong \frac{1}{R_1 + R_2} \left(V_2 - \frac{V_1 \, R_2 + V_2 \, R_1}{R_1 + R_2} \right)$$

LET K_3 = TEMPERATURE COEFFICIENT OF THE ZENER DIODE (V_3).

$$\frac{\Delta V_3}{V_3 \;\; \Delta T_Z} = \pm K_3$$

$$\frac{\Delta V_3}{V_3} \bigg|_{CR_1} \bigg|_{T} = \pm K_3 \, \Delta T_Z$$

$$\frac{\Delta V_3}{V_3} \bigg|_{T} = \pm \left[\frac{A_2 \, A_3 \, K_2 \, V_4 \;\; \Delta T_A}{V_3} + \frac{A_3 \, K_1 \, V_1 \;\; \Delta T_A}{V_3} + \frac{K_2 \, R_1 \;\; \partial V_3}{\partial R_1} \; \frac{\Delta T_A}{V_3} + K_3 \, \Delta T_Z \right]$$

$$\boxed{\left.\frac{\Delta V_3}{V_3}\right|_T = \pm\left[(K_1 V_1 A_3 + K_4 V_4 A_2 A_3)\frac{\Delta T_A}{V_3} + \frac{K_2 R_1}{V_3}\frac{\partial V_3}{\partial R_1}\Delta T_A + K_3 \Delta T_Z\right]}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{R_1} \cong \frac{\partial V_3}{\partial R_1}\frac{\Delta R_1}{V_3}$$

$$V_3 = \frac{V_1 R_2 R_3 + V_2 R_1 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

$$\frac{\partial V_3}{\partial R_1} = -\frac{V_1 R_2 R_3 (R_2 + R_3)}{D^2} + \frac{V_2 R_3}{D} - \frac{V_2 R_1 R_3 (R_2 + R_3)}{D^2}$$

WHERE $D = R_1 R_2 + R_2 R_3 + R_1 R_3$

$$\frac{\partial V_3}{\partial R_1}\cdot\frac{1}{V_3} = \frac{\dfrac{V_2 R_3}{D} - \dfrac{(V_1 R_2 R_3 + V_2 R_1 R_3)(R_2 + R_3)}{D^2}}{\dfrac{V_1 R_2 R_3 + V_2 R_1 R_3}{D}}$$

$$\boxed{\frac{\partial V_3}{\partial R_1}\cdot\frac{\Delta R_1}{V_3} = \left(\underbrace{\frac{V_2}{V_1 R_2 + V_2 R_1}}_{\text{TERM 1}} - \underbrace{\frac{R_2 + R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}}_{\text{TERM 2}}\right)\Delta R_1}$$

FOR THE CIRCUIT VALUES OF FIGURE 1, $R_1 \gg R_2$ AND $R_3 \gg R_1$, SO TERM 2 $\cong \dfrac{1}{R_1}$.

$$\left.\frac{\Delta V_3}{V_3}\right|_{R_1} \cong \left(\frac{V_2}{V_1 R_2 + V_2 R_1} - \frac{1}{R_1}\right)\Delta R_1 = \frac{-V_1 R_2}{R_1 (V_1 R_2 + V_2 R_1)}\Delta R_1$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{R_2} \cong \frac{\partial V_3}{\partial R_2}\frac{\Delta R_2}{V_3}$$

$$\frac{\partial V_3}{\partial R_2} = \frac{D\,V_1 R_3 - (V_1 R_2 R_3 + V_2 R_1 R_3)\ (R_1 + R_2)}{D^2}$$

$$\frac{\partial V_3}{\partial R_2}\cdot\frac{1}{V_3} = \frac{D\,V_1 R_3 - (V_1 R_2 R_3 + V_2 R_1 R_3)\ (R_1 + R_2)}{D^2} \times \frac{D}{V_1 R_2 R_3 + V_2 R_1 R_3}$$

$$\boxed{\frac{\partial V_3}{\partial R_2}\frac{\Delta R_2}{V_3} = \left(\frac{V_1}{V_1 R_2 + V_2 R_1} - \frac{R_1 + R_3}{D}\right)\Delta R_2}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{I_1}$$

$$I_1 = I_2 + I_3 = \frac{V_3 - V_2}{R_2} + \frac{V_3}{R_3} = \frac{V_3 R_3 - V_2 R_3 + V_3 R_2}{R_2 R_3}$$

$$V_3 = \frac{V_2 R_3 + I_1 R_2 R_3}{R_2 + R_3}$$

$$\frac{\partial V_3}{\partial I_1} = \frac{R_2 R_3}{R_2 + R_3}$$

$$\boxed{\left.\frac{\Delta V_3}{V_3}\right|_{I_1} = \left(\frac{R_2 R_3}{R_2 + R_3}\cdot\frac{R_2 + R_3}{V_2 R_3 + I_1 R_2 R_3}\right)\Delta I_1 = \frac{R_2}{V_2 + I_1 R_2}\,\Delta I_1}$$

APPENDIX B

ZENER DIODE STABILITY DATA

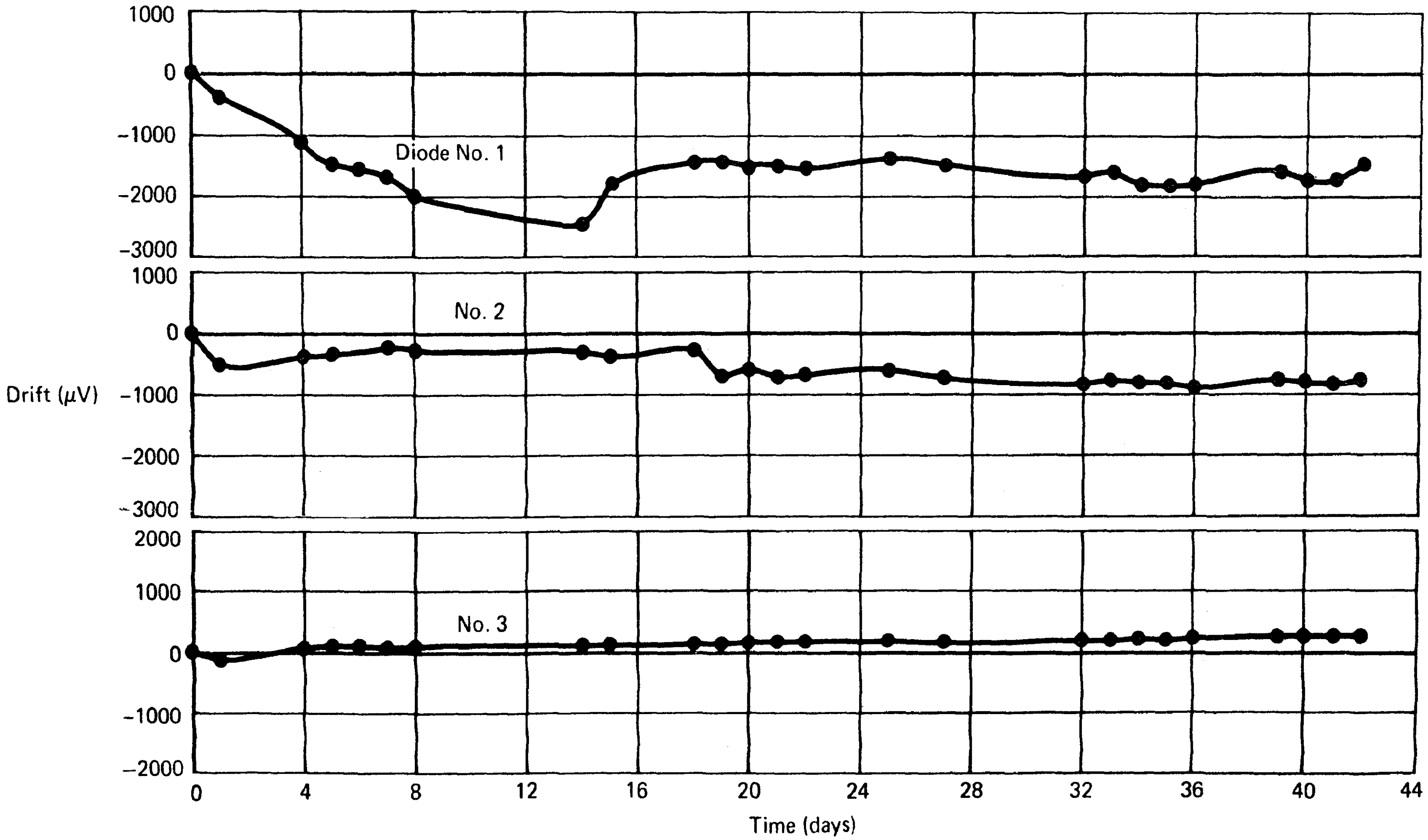

FIGURE 15. IN940B STABILITY WITH TIME

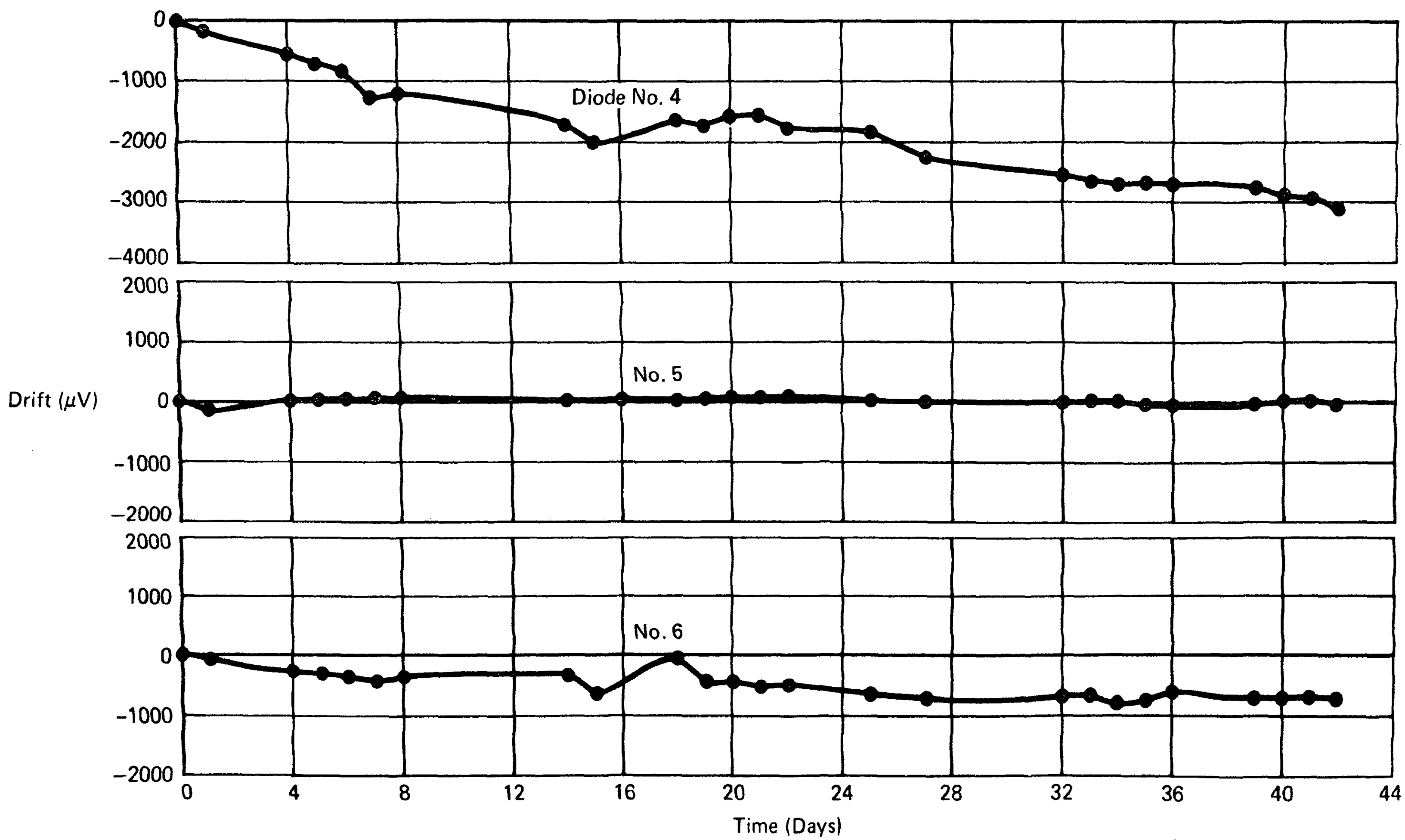

FIGURE 16. IN940B STABILITY WITH TIME

TABLE XIV

STABILITY DATA

Diode	Initial Value 8/27/70	Final Voltage 2/13/71	Change μV
1	9.306239	9.302710	-3529
2	9.164219	9.162800	-1419
3	9.088459	9.089170	+711
4	9.347279	9.344020	-3259
5	9.094835	9.094500	-335
6	9.276933	9.275900	-1033

TABLE XV

DIODE VOLTAGE VS TIME

Time	#1	#2	#3	#4	#5	#6	Date
1500					9.094855		8/27/70
1600	9.306239	9.164219	9.088459	9.347279	9.094835	9.276933	8/27/70
0815	9.305720	9.163310	9.088238	9.347098	9.094545	9.276880	8/28/70
1000	5960	3360	8380	7290	4720	7030	8/28/70
1300	5990	3970	8440	7170	4790	7040	8/28/70
1500	5890	4040	8450	7250	4800	7070	8/28/70
1630	5979	4139	8449	7039	4819	6949	8/28/70
1030	5094	3864	8534	6594	4844	6794	8/30/70
1200	5012	3992	8503	6512	4853	6622	8/31/70
1630	5020	3950	8510	6642	4850	6800	8/31/70
0800	4710	3670	8570	6650	4870	6710	9/1/70
1100	4610	3900	8530	6490	4856	6660	9/1/70
1400	4740	3930	8530	6440	4850	6760	9/1/70
1630	4680	4000	8540	6590	4880	6720	9/1/70
0830	4666	3710	8570	6620	4860	6606	9/2/70
1300	4530	3900	8542	6570	4860	6640	9/2/70
1600	4520	3960	8552	6250	4850	6660	9/2/70
0830	4630	3710	8560	6070	4880	6670	9/3/70
1100	4430	3970	8550	6060	4860	6650	9/3/70
1300	4420	4170	8540	5930	4860	6460	9/3/70
1600	4420	4160	8560	5970	4890	6530	9/3/70
0900	4220	3810	8590	6050	4880	6580	9/4/70
1100	4200	3910	8570	5900	4880	6661	9/4/70
1430	4190	4110	8570	6060	4880	6540	9/4/70
1030	9.304296	9.163846	9.088580	9.345520	9.094846	9.276630	9/10/70
1200	4490	3850	8600	5240	4850	6310	9/11/70
1645					4870		9/11/70
0830	4790	3570	8640	5670	4860	6580	9/14/70
1645					4890		9/14/70
0830	4790	3520	8640	5560	4870	6460	9/15/70

$T_A = 78°F$ $T_Z = 115°F$ (Diode #6)

TABLE XVI

DIODE VOLTAGE

Time	#1	#2	#3	#4	#5	#6	Date
1300					9.094890		9/15/70
1735			9.088660		9.094890		9/15/70
1030	9.304660	9.163660	9.088663	9.345600	9.094880	9.276490	9/16/70
1630					4880		9/16/70
0830	4720	3540	8670	5710	4870	6420	9/17/70
1300					4850		9/17/70
1645					4870		9/17/70
0830	4670	3530	8660	5450	4870	6420	9/18/70
1630	4670	3920	8655	5550	4880	6440	9/18/70
1500	4830	3610	8670	5430	4840	6220	9/21/70
1700					4870		9/21/70
1500	4690	3510	8680	4990	4860	6200	9/23/70
0830	4540	3400	8710	4650	4840	6200	9/28/70
1000	4610	3470	8720	4550	4850	6270	9/29/70
0900	4410	3440	8730	4480	4850	6110	9/30/70
1030	4370	3420	8710	4580	4810	6130	10/1/70
1000	4460	3350	8710	4530	4820	6350	10/2/70
0900	4690	3500	8770	4500	4810	6220	10/5/70
1000	4510	3470	8750	4340	4850	6220	10/6/70
1000	4500	3410	8780	4220	4840	6150	10/7/70
1100	4750	3500	8790	4140	4820	6270	10/8/70
1000	4580	3420	8790	4230	4830	6000	10/9/70
	3800	3000	8890	4390	4860	6000	11/3/70
	2490	2720	9030	3890	4580	5890	1/7/71
	2900	2550	9310	4240	4870	6200	1/8/71
		2720	9300	4330	4860	6070	1/9/71

APPENDIX C

ZENER DIODE TEMPERATURE TEST DATA

TABLE XVII

ZENER DATA VS TEMPERATURE

#1 V_3	#1 Noise μV	#2 V_3	#2 Noise μV	#3 V_3	#3 Noise μV	Date	TA Temp. (°F)	T_Z (#6) (°F)
9.302730	400	9.163430	1300	9.089330	580	1/9/71	87	118
9.302790	400	9.163530	1290	9.089270	565	1/11/71	87	118
9.300970	380	9.167110	1390	9.089940	620	1/11/71	120	138
9.299020	380	9.170900	1460	9.088450	640	1/11/71	142	161
9.296840	360	9.173760	1475	9.088190	650	1/11/71	166	184
9.302910	400	9.163410	1250	9.089240	550	1/12/71	87	118
9.302700	400	9.164280	1250	9.089300	550	11/13/71	87	119.5
9.298330	400	9.172120	1250	9.088380	550	11/13/71	87	117
9.303160	400	9.163960	1250	9.089520	550	1/14/71	87	117

TABLE XVIII

ZENER DATA VS TEMPERATURE

#4 V_3	#4 Noise	#5 V_3	#5 Noise	#6 V_3	#6 Noise	Date	TA Temp. (°F)	T_Z (#6) (°F)
9.344130	490	9.094890	445	9.276150	880	1/9/71	87	118
9.344260	480	9.094830	445	9.275960	890	1/11/71	87	118
9.343270	470	9.094850	485	9.274950	865	1/11/71	120	138
9.341410	460	9.094680	500	9.273640	825	1/11/71	142	161
9.339760	460	9.094650	520	9.272480	780	1/11/71	166	184
9.344200	465	9.094810	435	9.275930	880	1/12/71	87	118
9.34440	465	9.094920	435	9.276000	880	1/13/71	87	119.5
9.341010	465	9.094750	435	9.273500	880	1/13/71	87	117
9.344610	465	9.095060	435	9.276240	880	1/14/71	87	117

APPENDIX D

PERFORMANCE PREDICTION CALCULATIONS

Calculations of the predicted values for the reference performance are shown below. Table D-1 is a summary of the circuit parameter values as specified by the manufacturer for each component, or a derived value such as A_3, the zener circuit line regulation, and measured values as obtained by the techniques described in section IV.

TABLE XIX

SUMMARY OF CIRCUIT PARAMETERS

PARAMETER	DESCRIPTION	CALCULATED OR SPECIFIED	MEASURED VALUE
A_1	Isolator Line Regulation	0.037	0.001
A_2	Preregulator Line Regulation	0.0015	0.165
A_3	Zener Circuit Line Regulation	0.02439	0.0191
R_1 Ohms	Zener Input Resistance	800*	799
R_2 Ohms	Zener Resistance	20	16.5
R_3 Ohms	Load Resistance	10^6	10^6
V_5 VDC	Input Voltage	28	28
V_4 VDC	Isolator Output Voltage	20	20
V_1 VDC	Preregulator Output Voltage	15	15.04
V_3 VDC	Reference Output Voltage	9	9.09
I_2 mA	Zener Current	7.50	7.50
K_1 PPM/°C	Preregulator T.C.	± 100	+60
K_2 PPM/°C	T.C. of R_1	± 2	-1.04
K_3 PPM/°C	T.C. of CR_1 (Zener)	± 2	-0.45
K_4 PPM/°C	T.C. of Isolator	± 100	+145
ΔT_A °C	Incremental Change in Amb. Temp.	± 60	± 60
ΔT_Z °C	Incremental Change in Zener Temp.	± 60	± 60
V_2 VDC	Zener Equivalent Voltage	8.85	8.866

*Select R_1 for I_2 = 7.50 mA as required for specified zener T.C.

CALCULATION OF $\left.\frac{\Delta V_3}{V_3}\right|_{V_5}$

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_5} = \frac{A_1 A_2 A_3 \quad \Delta V_5}{V_3} \qquad \text{EQUATION (3)}$$

FROM TABLE D-1

A_1 = +0.037 (SPECIFIED FOR ISOLATOR).

A_2 = +0.0015 (SPECIFIED FOR PREREGULATOR).

A_3 = +0.02439 (CALCULATED USING NOMINAL CIRCUIT VALUES).

V_3 = 9 (NOMINAL OUTPUT VALUE).

ΔV_5 = +1

$$\left.\frac{\Delta V_3}{V_3}\right|_{V_5} = \frac{(0.037)\ (0.0015)\ (0.02439)}{9} = +0.150 \text{ X } 10^{-6} = \underline{\underline{+0.150 \text{ PPM/VOLT}}}$$

BY EQUATION (12):

$$A_3 \cong \frac{1}{1 + R_1/R_2} = \frac{R_2}{R_1 + R_2} = \frac{20}{20 + 800} = 0.02439$$

CALCULATION OF $\left.\frac{\Delta V_3}{V_3}\right|_{T}$

$$\left.\frac{\Delta V_3}{V_3}\right|_{T} = \delta_1 + \delta_2 + \delta_3 + \delta_4$$

WHERE δ_1 = CHANGE IN OUTPUT DUE TO THE ISOLATOR.

δ_2 = CHANGE IN OUTPUT DUE TO THE PREREGULATOR.

δ_3 = CHANGE IN OUTPUT DUE TO R_1.

δ_4 = CHANGE IN OUTPUT DUE TO CR_1.

$$\delta_1 = \frac{(A_2)\ (A_3)\ (K_4)\ (V_4)\ (\Delta T_A)}{V_3} = \frac{(0.0015)\ (0.02439)\ (\pm 100)\ (20)\ (1)}{9}$$

$$= \pm 0.008 \text{ X } 10^{-6} = \pm 0.008 \text{ PPM/}^{o}\text{C}$$

$\Delta T_A = 1\ ^{o}C$

$$\delta_2 = \frac{(A_3)(K_1)(V_1)(\Delta T_A)}{V_3} = \frac{(0.02439)(\pm 100)(15)(1)}{9} = \pm 4.065 \text{ PPM/}^{\circ}\text{C}$$

$$\delta_3 = \frac{(K_2)(R_1)(\partial V_3/\partial R_1)(\Delta T_A)}{V_3} = \frac{(\pm 2)(800)(-61 \times 10^{-6})(1)}{9} = \pm 0.0109 \text{ PPM/}^{\circ}\text{C}$$

$$\delta_4 = (K_3)(\Delta T_Z) = \pm 2 \text{ PPM/}^{\circ}\text{C};\ \Delta T_Z = 1\ ^{\circ}\text{C}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_T = \pm 0.008 \pm 4.065 \pm 0.0109 \pm 2 = \underline{\underline{\pm 6.0839 \text{ PPM/}^{\circ}\text{C}}}$$

WHERE

$$\frac{\partial V_3}{\partial R_1} = \frac{1}{R_1 + R_2}\left(V_2 - \frac{V_1 R_2 + V_2 R_1}{R_1 + R_2}\right)$$

$$= \frac{1}{800 + 20}\left(8.85 - \frac{15 \times 20 + 8.85 \times 800}{800 + 20}\right) = -61 \times 10^{-6}$$

CALCULATION OF REFERENCE OUTPUT CHANGE WITH TIME:

$$\left.\frac{\Delta V_3}{V_3}\right|_{\text{TIME}} = S_1 + S_2 + S_3 + S_4$$

WHERE S_1 = CHANGE IN OUTPUT DUE TO THE ZENER.
S_2 = CHANGE IN OUTPUT DUE TO THE PREREGULATOR.
S_3 = CHANGE IN OUTPUT DUE TO THE ISOLATOR.
S_4 = CHANGE IN OUTPUT DUE TO R_1.

$S_1 = \pm 25$ PPM/1000 HOURS (ESTIMATE BASED ON AVAILABLE ZENERS).

$$S_2 = \frac{A_3 \Delta V_1}{V_3} = \frac{(0.02439)(\pm 0.005 \times 15)}{9} = \pm 0.000203 = \pm 203 \text{ PPM/1000 HOURS}$$

$$S_3 = \frac{A_3\, A_2\, \Delta V_4}{V_3} = \frac{(0.02439)\,(0.0015)\,(\pm 0.01 \times 20)}{9}$$

$$= \pm 0.813 \times 10^{-6} = \pm 0.813 \text{ PPM/1000 HOURS}$$

$$S_4 = \left.\frac{\Delta V_3}{V_3}\right|_{R_1} \cong \left(\frac{V_2}{V_2 R_1 + V_1 R_2} - \frac{1}{R_1 + R_2}\right) \Delta R_1 = (-19.9 \times 10^{-6})\, \Delta R_1$$

$$\frac{\Delta R_1}{R_1} = \pm 25 \text{ PPM/6 MONTHS (SPECIFIED TIME STABILITY FOR } R_1\text{).}$$

$$\Delta R_1 = \pm\, (5.8 \text{ PPM/1000 HOURS})\,(800)$$

$$= \pm\, 4600 \times 10^{-6} \text{ OHMS/1000 HOURS}$$

$$S_4 = (-19.9 \times 10^{-6})\,(\pm 4600 \times 10^{-6}) = \pm\, 0.0915 \times 10^{-6}$$

$$= \pm\, 0.0915 \text{ PPM/1000 HOURS}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{\text{TIME}} = \pm 25 \pm 203 \pm 0.813 \pm 0.0915 = \underline{\underline{\pm\, 228.9045 \text{ PPM/1000 HOURS.}}}$$

CALCULATION OF REFERENCE OUTPUT NOISE:

$$\left.\frac{\Delta V_3}{V_3}\right|_{\text{NOISE}} = \sqrt{N_1^2 + N_2^2 + N_3^2}$$

WHERE N_1 = NOISE IN OUTPUT DUE TO CR_1.

N_2 = NOISE IN OUTPUT DUE TO THE PREREGULATOR.

N_3 = NOISE IN OUTPUT DUE TO THE ISOLATOR.

$N_1 = 55\ (\text{PPM})_{P\text{-}P}$ (MEASURED VALUE -- SEE DISCUSSION).

$$N_2 = \left.\frac{\Delta V_3}{V_3}\right|_{V_1} = \frac{A_3}{V_3}\, \Delta V_1$$

$\Delta V_1 = 0.00005 \times 15 = 0.00075\ V_{P\text{-}P}$ (PEAK-TO-PEAK NOISE OUTPUT FROM THE PREREGULATOR).

$$N_2 = \frac{(0.02439)\,(0.00075)}{9} = 2.03 \times 10^{-6} = 2.03\ (\text{PPM})_{P\text{-}P}$$

$$N_3 = \left.\frac{\Delta V_3}{V_3}\right|_{V_4} = \frac{A_2 A_3}{V_3} \quad \Delta V_4$$

$\Delta V_4 = 0.480 \ V_{P-P}$ (SPECIFIED PEAK-TO-PEAK NOISE OUTPUT FROM THE ISOLATOR).

$$N_3 = \frac{(0.0015)\ (0.02439)\ (0.48)}{9} = 1.92 \times 10^{-6} = 1.92\ (\mathrm{PPM})_{P-P}$$

$$\left.\frac{\Delta V_3}{V_3}\right|_{\mathrm{NOISE}} = \sqrt{55^2 + 2.03^2 + 1.92^2} = \underline{\underline{55.1\ (\mathrm{PPM})_{P\text{-}P}}}$$

A SUMMARY OF THE REFERENCE PERFORMANCE PREDICTIONS IS GIVEN IN TABLE VI.

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